40. RADIO ASTRONOMY (RADIO ASTRONOMIE)

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I. INTRODUCTION.

Harry van der LAAN, Leiden Observatory.

At the XVIth General Assembly, Commission 40 decided to curtail its triennial reports, confining them to aspects and developments which do not naturally find a place in the report of another commission. In letters to Presidents of eighteen commissions our new policy was explained and Commission 40 members willing to serve as radio astronomy contact person with one of these commissions were introduced. All Commission 40 members received notice of our intentions, with the names of the contact persons and an outline of this report in September 1978. We trust that from now on research at radio observatories will be integrally reported in the thematically appropriate reports of relevant commissions.

This report emphasizes basic radio measurements, techniques, the development of new facilities and observational perspectives. It does not include detailed compilations of new results nor provide comprehensive bibliographies. It is our hope that the information the report provides about opportunities in the near future as much as about recent achievements, will make it useful and justify the efforts its authors have so generously made.

More than half the report was written by members of the organizing committee, but several other commission members helped to complete it. Richard Schilizzi of the Dwingeloo Observatory designed the tables in section IV.d and wrote the European ones, matched by the American equivalents provided by the section's author. I thank all these colleagues for their fine cooperation. The editing necessary for the various parts has been of a minor nature and the credit for each section's contents belongs to its author. The overall scope and layout are my responsibility; it remains to be seen whether astronomers in general and radio observatories' staff in particular find this changed character of our report satisfactory.

In keeping with the practice begun six years ago, we have compressed the bibliographic references to forms minimally necessary for reader recognition. Keys may be found in the 1973 and 1976 reports. Not completeness or even balance have been our goals, but only to be informative within restrictions of time and number of pages.

II.a) SURVEYS

Roberto FANTI; Bologna.

The present report covers the period 1976 - October, 1978. It refers to only basic radio surveys, either wholly unbiased or made with reference to other radio data.

Galactic surveys.

A low frequency survey (2-20 MHz) of the galactic plane, in the galactic center region, has been made by Cane et al. (77 MN 179, 21). Brouw et al. (76 AA Sup 26, 129) presented a polarization survey of the background radiation at five frequencies, between 408 and 1411 MHz. Higgs (77 AJ 82, 329) has completed a 10 GHz survey of the Cygnus X region. Felli et al. (77 AA Sup 27, 181) used a fan-beam survey at 408 MHz for a systematic survey of extended sources (> 10 arcmin.) in the galactic plane. A survey of the galactic plane in the southern hemisphere, at 5 GHz, has been made at Parkes (Haynes et al. 78 AJP Ap Sup 45, 1).

Extra-galactic surveys.

A comprehensive account of the matter may be found in the Cambridge IAU Symposium no. 74. This is particularly useful since it gives general information on a number of surveys which have been going on for several years, but with no published data yet. Among these, those of particular interest are: 1) the low frequency survey at 151 MHz at Cambridge (6C) which is expected to be particularly powerful in detecting steep spectrum low surface brightness sources; 2) the Texas survey (UTRAO) at 335-380 MHz, important in providing very accurate radio positions ($\sim$ 1 arcsec.) for small diameter sources; 3) the NRAO-MPIfR 5 GHz survey (S4) which has more than doubled the northern sky area surveyed at this frequency.

The extra-galactic source surveys which appeared in the literature in the last triennium are compactly summarized in the table at the end of this section.

The most significant results are from those surveys obtained by earth rotation synthesis techniques which produce, at the same time, samples of sources very deep in flux with a high degree of completeness and reliability plus good radio positions for optical identifications purposes and useful angular structure information. These results have rejuvenated the interest in "source counts" for cosmological purposes.

Besides the aforementioned surveys, it is worth mentioning two compilations which are likely to be rather useful. The first is a revision of the 3CR Catalogue in terms of resolution and confusion effects (Veron 77 ESO Sci. Prepr.6). After applications of flux corrections and inclusion of a few other sources, the catalogue contains 205 sources above the flux limit of 9 Jy.

The second compilation is an "Index of extra-galactic radio sources catalogues" (Kesteven et al. 77 JRASC 71, 21) which may enable the reader to discover the original catalogue corresponding to any radio source name likely to be found in the literature.

Linear polarization measures of extra-galactic radio sources have been presented by Kronberg et al. (77 AJ 82, 688) at 3.7 and 11.1 cm and by Conway et al. (77 AA Sup 27, 155) at 6 and 21 cm. See also references therein. Comprehensive accounts on the general problematics connected to polarization studies are given in the Cambridge IAU Symp. no. 74

Freq. (MHz) Name	Min. flux (mJy)	Position accuracy arcsec.	Number of Sources	Sky area (ster.)	References
10-20 UTR 2	1500		329	1.8	Braude et al. 76 Prepr. 62 IRE AN USSR
408 MC 4	200	10	1340	.23	Clarke et al. 76 AJP Sup 401
408 MCdeep	90	10	468	.025	Robertson 77 AJP 30, 209, 231
408 5C6,7,8	20	5	214	.011	Wagget 77 MN 181, 547 Person et al. 78 MN 182, 273
610 WSRT	10	2	799	.03	Harris et al. 77 AA 60, 27 Valentijn et al. 77 AA Sup 28, 383 Katgert 78 AA Sup 31, 409 Harris et al. 78 AA Sup 34, 117
966	700	2	538	1.32	Cohen et al. 77 MRAS 84, 1
1400	30	15	106	.007	Halliday 77 MN 179, 111
1400 WSRT	10	2	1320	.033	Van Vliet et al. 76 AA 47, 345 Willis et al. 77 AA Sup 25, 453
2700 PKS	250	15	1273	1.21	Wall et al. 76 AJP Sup 39, 1 Wright et al. 77 AJP Sup 41, 1
8085	400	30	65	.18	Seielstad et al. 78 AJ 83, 157

II.b) HIGH-VELOCITY CLOUDS

Aad N.M. HULSBOSCH; Nijmegen.

The attention for the high-velocity-cloud (HVC) phenomenon is growing and in recent years much information has been published, by observers as well as by theoreticians. For the papers of 1975 and earlier we refer to the report of Van Woerden (76 Transactions IAU XVIA, part 3, 91). A recent summary of observational properties of HVCs has been given by Hulsbosch (79 in Large-Scale Characteristics of the Galaxy, IAU Symp. 84, ed. W.B. Burton); a discussion of models, based on these properties, has been given by Oort and Hulsbosch (78 in Astronomical papers, dedicated to Bengt Strömgren, eds. A. Reiz and T. Andersen, p. 409).

A systematic survey of a large part of the south galactic hemisphere down to a detection limit $T_b \simeq 0.05$ K, covering a velocity interval from -1000 to +1000 km s^{-1} has recently been made by Hulsbosch (78 AA 66, L5). At this moment this $1^o \times 1^o$ survey is being extended to cover the whole Dwingeloo sky, i.e. $\delta > -18^o$. At the same time the southern hemisphere ($\delta < -10^o$) will be surveyed by Mirabel in Argentina with much the same parameters as the Dwingeloo ones. A comparable survey with a somewhat coarser grid has been carried out by Giovanelli (79 in IAU Symp. 84),using the 300-ft telescope of N.R.A.O. at Green Bank.

Much effort has been put into high-resolution studies of a number of HVCs, mainly with the large single-dish telescopes, with the main result that the existence of bright cores in HVCs appears to be a rather general feature (Hulsbosch 78 AA Sup 33, 383; Giovanelli, Haynes 76 MN 177, 525; 77 AA 54, 909; Cram, Giovanelli 76 AA 48, 39; Schwarz et al. 76 AA 52, 133). The main problem is that most cores cannot be resolved even by 100-m telescopes and therefore a few observations are being carried out with the new 21-cm line system at Westerbork. The objects investigated are a few bright cores in HVC 132+23-211 and a very sharp gradient in HVC 139+28-195.

The discussion on HVC models has concentrated on the question whether HVCs are galactic or extra-galactic (Eichler 76 ApJ 208, 694; Giovanelli, Haynes 76 BAAS 8, 394; Giovanelli 77 AA 55, 395; Giovanelli 78 in IAU Symp. 77. Membership of the Local Group has been put forward by De Vaucouleurs (76 R. Greenwich Obs. Bull 182, 177) and De Vaucouleurs and Corwin (75, ApJ 202, 327). The question of isolated intergalactic clouds of neutral hydrogen has been discussed by Haynes (79 in IAU Symp. 84). An actual decision on the distance can at present only be made when the high-velocity structure is clearly connected with an outside system, like the Magellanic Stream, or when it shows clear signs of interaction with the galactic halo like "stream A" (Giovanelli 78 in IAU Symp. 77; Oort, Hulsbosch 78 in Astronomical papers, dedicated to Bengt Strömgren. eds. A. Reiz and T. Andersen, p. 409). A comprehensive study on stream A has been published by Oort (78 Problems of Physics and Evolution of the Universe, ed. L.V. Mirzoyan, 259). Of the several proposed origins considered by Oort, the one which sees the HVCs as the result of a thermal instability in a large halo falling towards the galactic centre got special significance by Fabian and Nulsen's suggestion that the slow-moving filaments around NGC 1275 might be due to such a thermal instability (Fabian, Nulsen 77 MN 180, 479).

One of the best studied features is the Magellanic Stream (MS), running from the Magellanic Clouds to roughly $l,b = 90^o, -40^o$ (the Tip) where the radial velocity reaches -400 km s^{-1} with respect to the lsr. New detailed observations have been made by Mathewson (76 R. Greenwich Obs. Bull. 182, 217) and by Mirabel et al. (79 MN, in press). It is generally agreed that the MS belongs to the triple system Galaxy-Large and Small Magellanic Clouds, either as a tidal debris disrupted from the Magellanic Clouds after perigalactic passage (tidal model, Mathewson et al. 74 ApJ 190, 291) or as primordial gas clouds in the same orbit as the Magellanic Clouds (the primordial model, Mathewson, Schwarz 76 MN 176, 47P). In the tidal case it should be possible to observe faint A stars in the tip of the MS (Oort, private communication), which, according to most models, is not farther away than about 10 kpc. A number of computer models based on either or both of these models have been published (Fujimoto, Sofue 76 AA 47, 263; 77 AA 61, 199; Einasto et al. 76 MN 177, 357; Lin, Lynden-Bell 77 MN 181, 59; Davies, Wright 77 MN 180, 71; Fujimoto 79 in IAU Symp. 84).A possible association of certain members of the Local Group with the MS and other HVCs (Lynden-Bell 76 MN 174, 695; Kunkel, Demers 76 R. Greenwich Obs. Bull. 182, 241) has been disproved by observations of Hartwick and Sargent on the radial velocity of such members (Hartwick, Sargent 78, ApJ 22, 512). A new model in which the components of the MS are formed as the result of thermal instabilities in the wake of the Magellanic Clouds after passage through a hot halo of the Galaxy has been published by Mathewson et al. 77 ApJL 217, L5); it requires, however, a rather dense halo.

So far no positive detections of HVCs other than in the 21-cm line have been made. Schwarz and Wesselius(78 AA 64, 97) have made continuum observations of 3C58, a SNR at a distance of 8 kpc in the direction of HVC 131+1-200. They found no trace of absorption which indicates that either HVC 131+1-200 lies beyond 3C58, or its spin temperature is higher than 200 K. A possible absorption by HVC 66+8-128 in the spectrum of 4C33.48 has been reported by Payne et al. but this needs confirmation (Payne et al. 78 ApJL 221, L95). Searches for CO in a few of the densest cores of HVC 132+23-211 are now being done by Israel and De Graauw (private communication).

III. BASIC MEASUREMENTS

Henry P. PALMER; Jodrell Bank.

a) Flux density scales and radio spectra.

In radio astronomy the absolute scales of flux density are related to the four intense continuum sources. Many values are available between 10 GHz and 100 MHz and smaller numbers of values at reduced accuracy are available down to 10 MHz and up to 90 GHz. After linear interpolation the resulting scale errors are smaller than 2% at any frequency between 10 MHz and 10 GHz and about 5% between 10 GHz and 90 GHz. This work has been well summarized by Baars et al. (77 AA 61, 99). Temporal variations in the flux from Cassiopeia A and Taurus A have been studied in the USSR (Stankevich 77 Pis'ma v Astr. zh. 3, 349; Barabanov et al. 77 Pis'ma v Astr. zh. 3, 302; Vinyaykin, Razin 78 Astr. zh. in press).

Some spectral studies of individual sources have been published, such as McAdam & Schilizzi (77 AA 55, 67) and Gopal-Krishna & Swarup (77 MN 178, 265).

b) Radio variability.

Variability of radio sources at a wavelength of 18 cm has been reported by Webber et al. (78 AJ 83, 900). Variability has been summarized at 3.7 and 11.1 cm by Altschuler and Wardle (77 MN 179, 153) and Bridle et al. (77 AJ 82, 21); at 2.8 and 4.5 cm by Andrew et al. (78 AJ 83, 863); at 1.35 cm by Yefanov et al.(77 preprint); and at 3.3 mm by Hobbs and Dent (77 AJ 82, 257).

The report (Hunstead 72 AL 12, 192) that some sources are appreciably variable below 1 GHz has been followed up actively by McAdam in Sydney. He has prepared a list of 37 sources measured to be variable at 408 MHz or lower frequency. A supplementary list of 18 sources have been found to be variable at 962 MHz at Jodrell Bank (Stannard and Bentley 77 MN 180, 703), and a further 15 suspects are reported from observations at Bologna (Fanti et al. 78 preprint). In a few cases low frequency variability has been observed at the same time as high frequency observations of the source, but the results do not correlate well. The most rapid change detected to date is 40% within a few months.

c) Polarization.

An important catalogue of polarization studies was recently published by Tabara and Inoue (78 "A catalogue of Linear Polarization of Radio Sources", Utsunomiya and Nagoya Universities). A polarization monitoring programme at Parkes was also set up for the regular observation of 26 sources at 5 GHz (Komesaroff et al. 78 Internal Report CSIRO, Sydney). A analysis of polarization distributions for 114 quasars at three frequencies was published by Miley and Hartsuijker (78 AA Sup 34, 129). For further advances in the study of total intensity and polarization variations, regular cooperative multifrequency monitoring programmes will probably be required.

d) Angular size measurements.

Observations with the 5km synthesis telescope at Cambridge have continued at 2.7, 5 and 15 GHz. A paper on the structure of 104 extragalactic sources at 5 GHz appeared recently (Jenkins et al. 77 MRAS 84, 61). A few measurements at 15 GHz have been published, for example on the quasars 270.1 and 275.1 (Riley and Pooley 78 MN 184, 769). The instrument is expected to be used at 30 GHz in the winter of 1979/80.

The synthesis telescope at Westerbork has continued in full use; recent substantial papers, in addition to Miley and Hartsuijker (78 AA Sup 34, 129) cited above, include Willis and Miley (78 AA Sup in press) on survey work at 6 cm, Tielens et al. (78 AA in press) on 4C sources with steep spectra, and Katgert

(76 AA 49, 221), Oosterbaan (78 AA 69, 235) on the angular size distributions of deep 21 cm samples.

The VLA in New Mexico and the 100km interferometer at Jodrell Bank, which both should be completed by 1980, will be very powerful instruments for the study of angular structures of line and continuum sources, and for astrometric purposes.

The determination of angular sizes for statistical studies has continued, using occultation (Venkatakrishna and Swarup 78 MASI in press) and interferometric techniques (Anderson et al. 78 Nat 271, 636). The θ-z and θ-S relations have been examined in more detail by Speed & Warwick (78 MN 182,761). It now seems to be generally agreed that compact sources are most common at around 1 flux unit, and it is likely that the proportion of small sources decreases again at lower fluxes. They also discuss the correlation between these results and the work on number counts.

Results from VLBI observations between the USA and the Crimea have been published (Pauliny Toth et al. 78 Pis'ma v Astr. zh. 4, no. 2).

e) Pulsars.

The number of known pulsars (now 304) was more than doubled by the publication of the Molonglo survey (Manchester et al. 78 MN 185, 409). A second case of optical pulsing was confirmed with the work on the Vela pulsar (Wallace et al. 77 Nat 266, 692).

The work on the proper motions of six pulsars reported by Anderson et al. (75 Nat 258, 215) has continued, and improved values for these, and measurements on 20 others, will be reported shortly (Anderson et al. 79 MN in preparation).

IV. RADIO TELESCOPES

a) Single dishes.

Jaap W.M. BAARS; MPI, Bonn.

Improvements of existing telescopes. - The new surface and improved feeds of the 305 m spherical reflector at the Arecibo Observatory (Puerto Rico) are being exploited to wavelengths as short as 6 cm. First experiments with an actively controlled deformable subreflector on the NRAO 43 m telescope to counteract large-scale astigmatic deformations in the main reflector have more than doubled the aperture efficiency at 1.35 cm. Thermal shielding of parts of the telescope have reduced pointing errors by a factor five. The telescope is now well suited for use at 1.35 cm. The surface of the 100 m telescope of MPIfR (Effelsberg/Bonn) has been partially readjusted for optimum performance at 40° elevations on the basis of the calculated structural deformations. A marked improvement has been achieved confirming at the same time the reliability of the homology-deformation calculations. Observations at 7 mm are planned in 1979. The Parkes telescope in Australia has been further improved by the installations of accurate reflector panels over the inner 17 m diameter, resulting in an aperture efficiency of > 40% at 7 mm and 16% at 3.3 mm. The efficiency at 1.35 cm is now 33%, referred to a diameter of 37 m.

Observing techniques. - With the very high sensitivity of receivers and increased sophistication of backends and data processing methods small instrumental effects increasingly set limitations on the achievable accuracy of the observations. Spectroscopy suffers from "baseline ripple" caused by multiple reflections in the telescope and/or receiver frontend. These are difficult to trace and to remedy (Morris 78 AA 67, 221). Improvements in dynamic range in mapping and reduction of weather effects in sensitive observations have been realized in continuum observations. Sidelobe subtraction can be accomplished by taking maps at various hour angles in azimuth/elevation scanning coordinates and separating sky-fixed and telescope-fixed components. In this way a dynamic range of 30 dB has been achieved (Rech et al. 78 AA 69, 165). The well-known dual-beam switching technique for the removal of tropospheric fluctuations has been successfully applied to the mapping of extended sources (Emerson et al. 79 AA in press).

Systematic "interference" in dual-beam observations caused by the space frame support of a radome has been found. These effects can be minimized by a second observation in which the horns traverse exactly the same hour angle range, while the source is located in the other beam (Tiuri and Urpo 78 Report S 108, Radio Lab, Helsinki Uni. Techn.).

MM-astronomy suffers from the lack of calibrated telescopes. Particularly serious is the high uncertainty in the various CO-line maps at 115 GHz. A special calibration effort on some "standard sources" is urgently needed.

New telescopes. - The only major new facility for the cm and long mm wavelengths is the RATAN 600 telescope in the Caucasus, which was completed in 1976. This variable profile antenna with a diameter of 600 m allows simultaneous observations in up to 4 different directions. It is useable to 8 mm, perhaps even to 4 mm. The collecting area is 4-7.10^3 m^2, depending on wavelength and the beamwidth is 5" at 8 mm. In Torun, Poland, a 15 m telescope became operational in 1978. It is useable to 22 GHz and will become part of the European VLBI-Network.

The emphasis in new single dishes lies clearly in the millimeter range. Several telescopes, with diameters between 4 and 20 m and useable to wavelengths as short as 0.5 mm, have recently been completed. At least 4 large antennas are in an advanced planning or early construction phase. Table IV.1 presents the major data of millimeter telescopes. Surface accuracies of $\sigma \lesssim 0.1$ mm (rms) are being achieved in the smaller, and aimed at for the larger dishes. The Caltech 10.4 antenna is extremely accurate and is in effect the first submm telescope of large size. This is achieved by machining the surface under real-time control of a measurement of the reflector profile (Leighton 78 "A 10-meter telescope for millimeter and sub-millimeter astronomy". Report California Inst. of Technology).

The SRC (British), NRAO (USA) and MPI (German) designs reach $D/\sigma \gtrsim 3.\ 10^5$, pointing accuracies of 1" and limiting wavelengths near 1 mm. These instruments will be placed on sites of high quality. The major characteristics of these designs are shown in Table IV.2.

The major problems in the realization of this performance are: gravitational deformation, differential temperatures through the construction, wind influence on pointing and deformation, surface panel manufacture and reflector contour measurement and setting.

Gravitational deformations are controlled by applying a homologous structure; wind effects are minimized by either a very stiff construction or by protection from an astrodome. Thermal effects are difficult to avoid: strong air circulation inside the dome is necessary. The exposed MPI-design is covered by insulating material, limiting daily temperature changes to < 1 K. Panels of $\lesssim$ 50µm rms accuracy are manufactured by machining or forming on a shaped template. Aluminium honeycomb with thin aluminium skin shows a very good thermal behaviour. Several methods for measuring and setting reflector panels to < 50µm accuracy are under development, but no method can yet reach this accuracy routinely. Promising developments are curvature and slope measurements (NRAO), distance variation by laser interferometer (SRC) and distance by laser ranging (MPI). Radio-holography should be further developped with radio sources, since it would provide a fast measurement at arbitrary elevation angle and so lead to an optimum setting of the reflector in its major elevation range (Bennet et al. 76 IEEE Trans. Ant. Prop. 24, 295), (Scott and Ryle 77 MN 178, 539.

Construction of the 45 m telescope in Japan was started in 1978. It will be used from 1-90 GHz and it represents a general purpose instrument offering a sizeable collecting area for cm wavelengths observations and a minimum wavelength in the middle mm-range.

The Caltech 10 m and SRC 15 m antennas are the first sub-mm telescopes significantly larger than the optical and IR telescopes, which are used now for the sub-mm range. Observations with these instruments have shown the feasibility of groud-based work in the atmospheric windows to 350µm wavelengths. It seems safe

Table IV.1 Millimeter telescopes

Telescope	Date	D [m]	σ [mm]	D/σ	λ_{min} [mm]	alt [m]	A at 100 GHz [m^2]	Remarks
CSIRO - Australia	1977	4	.09	44 000	1.5	0	6.5	$(\lambda_{min} = 16\ \sigma)$
U.Brit.Col. - Canada	1975	4.5	.13	35 000	2.0	0	7	
Aerospace - California	1963	4.6	.08	58 000	1.3	0	9	existing telescopes
McDonald Obs - Texas	1967	4.9	.09	52 000	1.5	2070	10	useable well above
Hat Creek - California	1968/74	6.1	.13	46 000	2.0	1050	13	100 GHz
Bell Tel. - N. Jersey	1977	7.0	.10	70 000	1.6	100	20	all are open or
Caltech - California	1978	10.4	.035	300 000	0.5	1200	50	in astrodome
NRAO - Arizona	1967	11.0	.14	74 000	2.2	1920	41	
Crimea - USSR	1966	22.0	.25	88 000	4.0	500	76	open
Mac Kenzie U. - Brasil	1972	13.7	.30	45 600	4.8	600	15	
Helsinki - Finland	1974	13.7	.3	45 600	4.8	0	15	all ESSCO antennas
Yebes - Spain	1976	13.7	.2-.25	≈60 000	≈3.5	1000	≈30	in closed radome
Onsala - Sweden	1976	20.0	.18	110 000	2.9	0	105	(transmission t=0.83
Amherst - Massachusetts	1977	13.7	.15	91 000	2.4	500	50	at 100 GHz)
SRC (Eng) - Spain (?)		15.0	.05	300 000	.8	≈3000	100	
NRAO - Hawaii	early	25.0	.07	355 000	1.1	4080	270	all in planning phase;
MPI - Spain	80's	30.0	.09	335 000	1.4	~3000	370	open or astrodome
SRC (Jap) - Japan		45.0	.3	150 000	4.8	1350	200	
		(20.0	.2	100 000	3.2	1350	94	inner part of 45m tel.)

Table IV.2 Characteristics of three large mm-telescope designs (from the internal design reports)

		SRC/United Kingdom	NRAO/USA	MPIfR/Germany
Reflector Diameter	[m]	15	25	30
Mounting and drive		alt-azimuth	alt-azimuth	alt-azimuth
		wheel-on-track in az. direct in alt.	wheel-on-track; alt. bull-gear	alidade; alt. double bull gear
Protection against environment		Astrodome with membrane	Astrodome with "transparent" door	Exposed - structure thermally insulated
Site-altitude [m] - latitude	[o]	Spain - 2500 - 27 or - 3000 - 37?	Hawaii - 4080 - 20	South. Spain - 3000 - 37
Weight elevation structure	[kg]	16 500	75 000	475 000
Weight of protection	[kg]	360 000	370 000	45 000
Surface panel - type, number		Alu honeycomb, 144	Alu machined, 528	Alu honeycomb with adjustment, 420
- rms accuracy	[μm]	25	40	40-50
Deformation - peak	[mm]	1.4	5	6
change in focal length	[mm]	0.75	2.8	3.5
homology + tolerances (rms)	[μm]	20	20	50
thermal + wind (rms)	[μm]	20	20	27
Total surface error rms	[μm]	50	70	90
Pointing error	[arc sec]			
tracking		2	1	1
wind		0.1	0.1	2
Highest frequency	[GHz]	550	400	300
HPBW at highest freq.	[arc sec]	9.0	7.5	8.2
Collecting area at max. freq.	[m^2]	28	75	118

to predict, that the next "Reports on Astronomy" will list several new telescope projects for the sub-mm region. It is important that at least one sub-mm telescope of large size be located in the Southern Hemisphere.

b) Millimeter interferometers and arrays. Emile J. BLUM; Meudon.

Introduction. - Millimeter wave interferometers and arrays are in a period of development, and significant progress has taken place during the last three years. However most present instruments work at the upper edge of the millimeter band; at higher frequencies there are more tests and projects than operating systems. The published data are still scarce and much information is coming from conferences or private communications.

Millimeter interferometers and arrays have the same problems as mm single dishes, plus the specific problem of phase coherence. In particular the local oscillator transmission should be phase stable, and various solutions have been proposed. No direct information is available yet on the differential phase fluctuation caused by the atmosphere on a signal reaching two antennas, but reasonable extrapolations for low altitude sites are obtained from centimeter instruments, and in particular from the 5 km Cambridge interferometer (Ryle 72 Nat 229, 435; Hargrave and Shaw 78 MN 182, 233) used at 15 GHz. Phase stable operation can be expected for a reasonable fraction of the time at 100 GHz, with a 500 m baseline.

Solar observations. - The instruments designed for solar observations appeared first. They use relatively small dishes and simple receivers, because the sensitivity is not critical. Up to now their resolving power is moderate and therefore there is little effect from the atmosphere. Three instruments are currently in use, all in the 35 GHz region.

The interferometer at Bordeaux, described in 73, has been used since then in particular for the study of bright sources (Bocchia and Poumeyrol 76 ApJ 204, 107). The interferometer at Table Mountain (altitude 2300 m) (Janssen and Olsen 79 ApJ March 1, in press) began operation in 1974 and observes the Sun and the planets. It uses two unequal size antennas (5,5 and 3 m diameter), on EW baselines of 60 or 120 m. The local oscillator reference signal is transmitted to each antenna at 12 GHz through a flexible elliptical waveguide. The instrumental phase shift rarely exceeds 20° per hour. The array of 50 cm dishes at Nagoya (Kawabata et al. 74 PASJ 26, 387; Kawabata et al. 77 UAG report for 7-24/9 and 22/11/77, NDAA, Boulder, Col. in press) has been recently extended by doubling the number of antennas to 16, and the length of the baseline to 50 m. The local oscillator is transmitted to the four receivers by oversized rectangular waveguide. The overall system phase error is 10°.

In Australia a prototype has been successfully tested (Labrum 78 PASA, in press). It uses two 30 cm dishes, on a baseline variable up to 6 m. The center frequency is 100 GHz. The two receiver klystrons are phase locked to a common source through an elaborate system using coaxial cables. A larger 100 GHz interferometer is under construction; it will use a 4 m and a 2 m dish, on an initial baseline of 90 m, and will observe fine structure in the solar brightness distribution.

All purpose instruments. - We should first note that the 5 km interferometer at Cambridge will be soon used at 30 GHz. The VLA which is also not a specific millimeter instrument begins operation at 22 GHz.

The two antenna interferometer at Hat Creek (Welch et al. 77 AA 59, 379) has been extensively used at 22 GHz and tests at 88 GHz have begun in 1978. The interferometer has two 6 m diameter dishes, with a surface accuracy of ∿ 0,12 μm, and the dishes may be moved to a number of stations along a 300 x 200 m EW -NS T. The local oscillator reference is transmitted at 400 MHz through coaxial cable. No information is available yet on the phase stability of the system and of the atmosphere at 88 GHz.

At the Owens Valley Observatory (Cal. USA) Cal Tech scientists (R. Leighton, A. Moffet) are building a three element interferometer, with 10.4 m diameter dishes.

The initial baseline will be 60 m and the frequency 80 - 120 GHz. Operation at much higher frequency and longer baselines will be possible. The local oscillator reference frequency will be carried by coaxial cable. The altitude of the site is 1200 m; operation of the first pair of antennas is expected for 1979.

Two other projects are at a less advanced stage. In Japan the site development (1400 m altitude) for a 45 m single dish and a 5 x 10 m array on cross baselines is just beginning. The system will work at 115 GHz, completion is expected for 1981-82.

In Europe, within the framework of a joint German-French Institute, the financing of an array of 3 to 4 antennas, each of approximately 12 m diameter,has been decided. The site (altitude 2500 m) will be higher than in the other projects. The initial baseline will be about 500 m; operation at 115 GHz and eventually higher is planned.

Sites for millimeter astronomy. - A site for mm astronomy should in principle meet the same requirements as that for a normal Radio Astronomy Observatory, with the extra condition of limited atmospheric effects: mm waves are absorbed by the atmospheric water vapour and by most clouds.

Together these requirements are sometimes contradictory: in particular little water vapour means altitude and cold, whereas operation is eased by proximity to developed areas.

Some recent work allows a better estimate of these atmospheric effects. Plambeck (78 IEEE Trans, Ant. & Prop. AP. 26, 737-738), Wrixon and Mc Millan (78 IEEE Trans Microwave Theo. & Tech. MTT 26, 434-439) give the absorption of 230/225 GHz waves versus atmospheric water vapour content. The general distribution of this content is reasonably well known, but that for a given location less so: Hansen & Caimanque (75 PASP 87, 935-939), Roosen & Angione (77 PASP 89, 814-822) have studied the case of some optical observatories: their results are interesting and show that a knowledge of the general distribution of water vapour or of humidity at ground level does not allow a precise estimate of the water vapour content over a given site, at least in mountain areas.

The weight of practical considerations is such that most present mm observatories are at low or moderate altitude. This does not degrade significantly the sensitivity of present receivers. The situation will change with improved receivers, and several high altitude sites are being considered for future observatories.

c) Aperture synthesis telescopes.

Edward B. FOMALONT; NRAO.

This report covers both aperture synthesis techniques used in radio astronomy: earth-rotation synthesis arrays which are designed to utilize the rotation of the earth to form radio maps and image synthesis arrays from which good quality maps are formed instantaneously. Some arrays can operate in both manners. Arrays operating above 40 GHz frequency will not be covered here.

The major aperture synthesis telescopes now in use or in construction are listed in the Table. All of the arrays with only an E/W baseline must observe a source (above 20 deg declination in the same hemisphere) over a period of 12 hours in order to form a good image. Arrays with a more complicated geometry can produce good quality maps over a larger region of sky in a shorter period of time. The table contains only the bare outline of the capability of the arrays. Spectral line, narrow band operation of the array is indicated by (SL) in the operating frequency column.

The report deals with the following aspects: (1) Design of aperture synthesis arrays; (2) Calibration of arrays; (3) Mapping techniques and problems; (4) Map restoration; (5) Troposphere and ionosphere problems, and (6) The next three years.

Design of aperture synthesis arrays. - The quality of an image which an array obtains is directly related to the completeness of coverage of the synthesized aperture. The problems and trade-offs are understood for E/W arrays which utilize the earth-rotation to form a 2-dimensional elliptical aperture (e.g. Ryle and

APERTURE SYNTHESIS

Institution	Location of Array	Number of Elements ( )=Movable
California Institute of Technology	Owens Valley, CA, USA	3 (3)
CSIRO	Culgoora, NSW, Australia	96
Dominion Radio Astrophysical Observatory	Penticton, BC, Canada	4 (2)
Indian Institute of Astrophysics	Bangalore, India	91
Mullard Radio Astronomy Observatory	Cambridge, UK	12 (4)
	Cambridge, UK	3 (2)
	Cambridge, UK	2 (1)
	Cambridge, UK	
National Radio Astronomy Observatory	Socorro, NM, USA	27 (27)
	Green Bank, WV, USA	4 (3)
Netherlands Foundation for Radio Astronomy	Westerbork, Neth.	14 (4)
Stanford University	Palo Alto, CA, USA	5
Tata Institute	Ooty, India	4
Tokyo Astrophysical Observatory	Nobeyama, Japan	5 (5)
University of Bologna	Medicina, Italy	2
University of California	Hat Creek, CA, USA	3 (3)
University of Manchester	Jodrell Bank, UK	6
University of Maryland	Clark Lake, CA, USA	48
University of Sydney	Fleurs, NSW, Australia	34
University of Texas	Marfa, TX, USA	5

a. Anticipated 1980 completion of 0.327 GHz and correlator mode operation.
b. Construction in progress. 90 N/S elements correlated with 1 E/W element.
c. 31 GHz operation testing in 1979.
d. 4.6 km 0.151 GHz array now under construction.
e. Completion date 1980; but operating with existing facilities.
f. Operation by the U.S. Naval Observatory for astrometric use.

TELESCOPES

Sizes of Elements (m)	Array Sizes and Configurations (km)	Operating Frequencies (GHz)	Comments
25, 40	0.5 N/S, 1.2 E/W	0.9 to 15 (SL)	
13	3 circular	0.04, 0.08, 0.16, 0.327	a
9	0.6 E/W	1.4 (SL)	
	1.5 E/W, 0.5 N/S	0.03	b
10	5 E/W	2.7, 5, 15, 31	c
	1.6 E/W	0.4, 1.4	
	0.8 E/W	1.4 (SL)	
	1.4 E/W	0.151	d
25	0.7, 3, 7, 21 'Y'	1.5, 4.9, 15, 22 (SL)	e
13, 25	2.7, 35 SW	2.7, 8.1 (SL)	f
25	3.2 E/W	0.32, 0.61, 1.4, 5.0 (SL)	g
18	0.2 E/W	10.2	
5, 13.5, 530	3.9 E/W	0.327	h
10	0.56 E/W, 0.52 NE	22 to 115 (SL)	i
	1.0 E/W, 0.4 N/S	0.408	
6	0.3 E/W, 0.2 N/S	20 to 88 (SL)	
15, 25, 70	1 to 127	0.4 to 22 (SL)	j
100	3 E/W, 1.8 N/S	0.02 to 0.12	k
6, 14	0.79 E/W, 0.79 N/S	1.4	
75, 300	3.0 E/W, 3.1 N/S	0.365	ℓ

g. 0.32 GHz operation scheduled for 1980.
h. 3 small antennas correlated with Ooty cylindrical antenna. Under construction.
i. Under construction. Will be used with 45-m antenna.
j. Array being expanded.
k. Each element consists of a bank of 15 'antennas'.
ℓ. More elements under construction.

Hewish 60 MN 120, 220). Equispaced elements used at Cambridge and Westerbork produce the highest quality images within the angular radius of the first grating ring. The diameter of the ring can be made large by moving a few of the elements and the resolution can be doubled with the addition of one element. The best resolution for a given number of elements is obtained by a minimum redundancy array (Stanford University Array; however, it is not expandable to lower or higher resolution unless nearly all elements are moveable. The Japanese (Ishiguro 78 A Report on Super-synthesis Telescope in Japan, Tokyo Astronomical Observatory) have determined a minimum redundancy array for five antennas in five configurations to obtain 64 non-redundant spacings.

Optimization of 2-dimensional arrays pose more of a problem. Instantaneous images are of good quality when a satisfactory distribution of spacings and position angles are sampled in an aperture, such as for cross-, tee-, circular-, wye-, pi- or square-shaped arrays. No simple optimization methods, apart from trial and error, have been devised for arrays which utilize earth-rotation to fill out the aperture. Chow (72 IEEE Trans. Ant. Prop. AP-20, 30) has investigated some of the general properties of such apertures.

Calibration of an array. - In order to make high quality maps, the signals from each element must be combined with a path-length error less than a small part of a wavelength, a timing error much less than the reciprocal bandwidth and knowledge of the amplification of the electronics to a few percent. Nearly all of the existing arrays use several calibration methods to measure or monitor various properties of the array. Signals from stable noise sources are injected into the array elements to monitor changes in the electronic system. The phase path-length in the lines between the elements are accurately measured by propagating a weak monochromatic radio signal along the links connecting the elements. Finally, external radio sources of small-angular diameter, known position and known flux density are frequently observed to monitor the overall array performance. This calibration is most useful in alleviating path-length variations caused by the tropospheric refraction in the atmosphere. For arrays larger than several kilometers, knowledge of the time to an accuracy of ∿ 1 ms are necessary.

Mapping techniques and problems. - The basic response of all arrays, the visibility function or spatial coherence function, is closely related to the Fourier transform of the radio source angular power distribution (e.g. Fomalont and Wright 74 Galactic and Extragalactic Radio Astronomy, Chap. 10, New York: Springer). The most obvious and widespread technique used to produce a radio map is, thus, by a Fourier transform of the visibility function (a complex quantity usually resolved into an amplitude and phase). For small arrays, this Fourier procedure can be efficiently performed in a moderate-sized digital computer, In some E/W arrays, the transform is made, instantaneously, in the radial dimension and the azimuthal dependence summed as the observations progress.

For large arrays (> 1000 element radii units across the array), the Fast Fourier Algorithm efficiently calculates maps of a large field of view in a reasonable time. However, application of this algorithm produces errors and distortions in the maps which can be serious. Computation methods for reducing these distortions are being investigated at Westerbork, the VLA and in Australia. The storage capacity and quick access of the visibility data in the computer, especially for arrays with multi-frequency capability, is a problem.

A technical detail which affects the large, non E/W baseline arrays is that the synthesized aperture is not planar. To obtain accurate maps, a 3-dimensional transform should be taken, or a series of 2-dimensional transforms (array apertures are nearly planar over a short period of time) summed. Both procedures are cumbersome and efficient algorithms are being developed.

Special purpose hardware and micro-circuits are being designed to compute the Fourier transform (Frater and Skellern 78 AA 68, 391). The possibility of recording the visibility data on film and then using optics to obtain the Fourier inversion is also being considered (ERIM 77 A Study for an Optical Processor System for VLA

Radio Telescope System).

Map Restoration. - The synthetic aperture obtained from arrays is far from perfect. As opposed to a continuous aperture distribution obtained from paraboloids, a synthetic aperture contains 1) discrete samples along an ellipse, 2) a hole in the middle, 3) asymmetries from non-E/W baselines, and 4) missing wedges. A host of techniques have been developed to restore a more correct image of the radio sky in view of the defects of the aperture.

The most successful technique, CLEAN (Högbom 74 AA Sup 15, 417), has been used at most observatories in conjunction with the Fourier mapping of the visibility function. The method can correct for much of the image distortion caused by the defects of the synthesized aperture. Recently, detailed mathematical analysis of CLEAN (Schwarz 78 AA 65, 345) has led to a better understanding of its limitations, convergence and uniqueness of solution. Computation optimization of the algorithm is being investigated to lessen the significant time taken in large computers. Also, special purpose hardware is being designed to implement CLEAN.

Investigations are proceding in other mapping processes which by-pass the Fourier transform. For radio source maps which can be described by a small number of parameters (small-diameter sources, planets), a reasonably accurate model of the source can be fit directly to the measured visibility function. Although time consuming in a computer, good results have been obtained. Several groups are now investigating the Maximum Entropy Method (MEM) as a technique for obtaining high quality maps (e.g. Warnecke and D'Addario 77 IEEE Trans. C-26, 351). MEM is successful with high signal-to-noise data for relatively simple radio sources. Development of much more efficient algorithms and a better understanding are necessary for more general use.

The hole in the center of a synthesized aperture causes serious map zero level changes for large-diameter sources. The hole can be filled by total power observations of an element in the array (usually with poor signal-to-noise) or by mapping of the radio source with a large paraboloid. Several techniques to complement single-antenna measurements with array measurements are now being pursued.

Atmosphere and ionoshere problems. - The dominant source of error in the radio map is caused by differential tropospheric refraction across arrays (e.g. Hargrave and Shaw 78 MN 182, 233; Hamaker 78 Radio Sc 13, 873.) with baselines greater than 2 km and frequencies above 2 GHz and by ionospheric refraction for similar baselines below 400 MHz frequency. The fluctuations vary on a time-scale of 30 seconds to several days and have a relatively small angular correlation length. The nature of the detailed tropospheric irregularities is unknown. Although there is some correlation with obvious water-vapor content and clouds, turbulence is probably a major factor. Excellent observing conditions occur during periods of extensive fog and relatively poor conditions can occur in dry climate in windy conditions. Occasionally large refractive wedges move across an array, often unassociated with a measurable meteorological phenomenon. A rough estimate of the magnitude of the troposheric refraction during good, stable conditions is about 3 mm path-length change for a ten--kilometer baseline with about a 20 minute time-scale. The magnitude and time-scale vary roughly with the square-root of the baseline length. During periods of inclement weather, 3 cm path-length changes occur. Plasma in the earth ionosphere cause serious phase errors over a large array at relatively low frequency. There is a sizeable day-to-night change and during enhanced solar activity, large changes occur on minute time-scales.

The water vapor content of the troposphere can be obtained by measurements at 1.3 cm of the water-vapor mission in the atmosphere. However, the accuracy in predicting the resultant path-length change caused by the water vapor is no better than 1 cm since the temperature of the water vapor cannot be obtained. This measurement does not determine the refraction caused by dry air. Measurements of the effect of the ionosphere refraction can be estimated by radio sonde measurements. When low frequency radiation is propagated through the ionosphere, the small part which is reflected back to earth can be used to determine the plasma density versus height.

The experimental technique which reduces the effects of atmospheric and ionospheric refraction variations is called "nodding". Observations are interlaced between the radio source being mapped and a nearby point calibrator. If the source-calibrator angular correlation is sufficiently small (< 10 deg), the phase fluctuations will be highly correlated. Some arrays can be separated into two parts, so that the source and calibrator can be observed simultaneously. Some low frequency arrays (e.g. Erickson and Fisher 74 Radio Sc 9, 387) can switch between sources in less than one second.

If the radio source itself contains a component which is sufficiently strong and unresolved, it may be used as a calibrator to determine the phase fluctuations. The success of this method requires that the response of the unresolved component be isolated from the remaining radio emission.

Computational methods are being developed from which good quality radio maps can be obtained in the presence of severe phase fluctuations. In several methods the visibility phase is ignored and an image formed by using only the visibility amplitude. Fitting a simple model of the source to the observed visibility amplitude is satisfactory for relatively simple sources. This technique is used extensively for VLBI data reductions. A Fourier inversion of the visibility amplitude squared produces a map which is an autocorrelation of the real map (Baldwin and Warner 78 MN 182, 411). Some success at Cambridge has been obtained with this phaseless aperture synthesis for radio maps composed of small-diameter components. Extension of MEM to phaseless data is possible but requires excessive computing time. A disadvantage to all amplitude-only-methods is that a signal-to-noise ratio > 3 is required for each data point and there are ambiguities in the orientation and symmetry of phaseless maps.

The use of closure phase, commonly used in VLBI, is now finding its way in conventional array synthesis (Readhead and Wilkinson 78 ApJ 223,25). If α_{ij} represents the measured visibility phase between elements (i_{ij}), ψ_{ij} represents all instrumental/tropospheric phase error, and ϕ_{ij} represents the true visibility phase, then the sum of the measured phases over each triad of antennas (i, j, k) is

$$\alpha_{ij} + \alpha_{jk} + \alpha_{ki} = \phi_{ij} + \phi_{jk} + \phi_{ki} + (\psi_{ij} + \psi_{jk} + \psi_{ki}).$$

The sum in parenthesis will add to zero for all phase contributions which are properties of an element rather than a pair of elements; i.e. if $\psi_{ij} = \psi_i - \psi_j$. All troposhere and ionosphere errors are element-based as are most phase variations caused by the electronics. Thus an accurate measurement of the sum of these visibility phases can be obtained.

Incorporation of phase closure data to produce a radio image is not straightforward. Model fitting and MEM can be used. The determination of the individual phases from the set of closure phase data requires additional information. In an n-element array there are n(n-1)/2 visibility phases but only (n-1)(n-2)/2 independent closure phase relationships. Several iteration schemes are being developed to incorporate *a priori* information with closure phase to obtain accurate visibility phases suitable for conventional Fourier analysis.

The next three years. - Aperture synthesis development in the next several years will probably emphasize the following lines:

(1) Improvement of dynamic range of radio maps. Because of the errors described previously, many maps, especially at high frequency and resolution (also at frequencies lower than 300 MHz) are limited in accuracy not by receiver noise but by spurious responses associated with bright sources in the map. Obtaining a dynamic range > 100:1 is often difficult. Efficient algorithms which are cognizant of the poor phase data, better calibration techniques and more accurate monitoring of tropospheric/ionospheric conditions are needed.

(2) Map distortion. Distortions in large-field-of-view maps caused by non planar apertures, by large operating bandwidths, and by the use of FFT are a problem for the VLA and low frequency arrays. Better computational methods are needed to lessen these distortions.

(3) Efficient data handling. The volume of data produced by arrays, especially those supporting spectral line systems, is enormous. Radio astronomers must be cognizant of the most up-to-date digital hardware to meet their needs.

(4) Low frequency arrays. There is growing astrophysical interest in high resolution maps under 400 MHz. The existing arrays in Cambridge, Culgoora (e.g. McLean IAU/URSI colloquium, Groningen, 1978, in press), India, Texas and Clark Lake are being improved. Technical problems associated with array design and ionosphere problems are unresolved. Conversion of high frequency arrays to meter wavelengths are not straightforward.

d) VLBI arrays. Alan T. MOFFET; Caltech.

To determine the structure of compact radio sources, arrays of very long baseline interferometers have been organized. By observing simultaneously at three or more stations, and by following the source over a wide range of hour angles, a fair sampling of the spatial frequency (u,v) plane may be obtained. So far these VLB arrays have used existing telescopes, selected to provide the best possible coverage of the u.v plane (Cohen 75 Caltech Report, VLBI network studies I). Results obtained in this way have been encouraging enough for several groups to begin plans for dedicated VLB arrays.

As was first pointed out by Rowson (62 MN 125, 177) the baseline between two antennas traces out an ellipse in the u,v plane as a source is tracked. When N antennas are simultaneously used, there are N(N-1)/2 such ellipses. With arrays of existing telescopes the u,v plane coverage is not uniform. Also, until recently only the amplitude of the visibility function was determined in VLB observations. These deficiencies make it impossible to map the source distribution by direct Fourier inversion of the observed visibility data; instead, sophisticated model-fitting computer programs have been developed (for example, Fort and Yee 76 AA 50, 19). In general, these are closely related to the CLEAN algorithm of Högbom (74 AA Sup 15, 417).

While visibility phase cannot be measured on any given baseline because of the unknown phase of the independent local oscillator at each station, there is an algebraic combination of the visibility phase around any triad of stations, in which the individual instrumental phases all cancel out (Roger et al. 74 ApJ 193, 293). This combination is called the *closure phase*. For an N station observation there are (N-1)(N-2)/2 independent closure phases. Fort and Yee (76 AA 50, 19) and Readhead and Wilkinson (78 ApJ 223, 25) have described ways to introduce these into iterative model-fitting programs. Closure phases have been successfully used at wavelengths as short as 2.8 cm (Readhead et al. 79 ApJ in press).

VLB arrays require groups of stations with compatible data recording terminals. The most widespread system is the digital NRAO Mark II (2 MHZ bandwidth). There are about 20 Mark II terminals in North America, Europe and Australia (Clark 73 Proc. IEEE 61, 1242). Mark II processors are presently in operation at NRAO, Charlottesville, and MPI, Bonn, both 3-station with spectroscopic capability and at Caltech, Pasadena, a 4-station continuum processor, presently being expanded to handle 5 stations.

Other recording systems currently in use are the Canadian analog video-tape system (Broten et al. 67 Sci 156, 1592), and the US Mark III, a new broad-band digital system based on multi-track instrumentation recorders (Whitney 78 VLBI Symposium, Heidelberg). A joint US-Canadian group has demonstrated the practicality of a real-time VLB interferometer using a satellite data link (Yen et al 77 Sci 198, 289).

The USA network of existing radio telescopes has operated for 3 years under semi-formal arrangements for scheduling and technical coordination (Cohen 75 Caltech Report VLBI network studies I). Its success has led to plans to fill in

Table IV.3(a). Observatories in the U.S. VLBI Network: System noise temperature (°K) and aperture efficiency listed as a function of wavelength on 1 July 1979.

Observatory	Antenna Diam.(m)	Observing wavelength (cm) 1.3	2.8	3.8	6	13	18	21	50
Fort Davis (Texas)	26		350 0.25	160 0.45	150 0.45		150 0.45		300 0.45
Green Bank (West Virginia)	43	60 0.25	70 0.45	85 0.50	70 0.50	150 0.50	60 0.50	50 0.50	200 0.45
Hat Creek (California)	26			220 0.41	60 0.50		90 0.50	75 0.50	
Haystack (Mass.)	37	120 0.22	80 0.36	75 0.40		150 0.20	200 0.20		
North Liberty (Iowa)	18						60 0.50	200 0.50	
Owens Valley (California)	40	120 0.30	80 0.50	160 0.50	120 0.50	120 0.50	75 0.60	75 0.60	300 0.45
Vermilion River (Illinois)	37					100 0.40	80 0.52		

Other observatories which are occasionally used for VLBI but which are not part of the VLBI network because of limitations on availability or coverage include: Algonquin Park (Canada),46m; Amherst (Massachusetts),15m; Arecibo (Puerto Rico), 300m; Goldstone (California), 64m, 26m; JPL Aries (California), 10m; and Maryland Point (Maryland), 26m.

Other wavelengths: Green Bank (2cm) 125/0.40, Haystack (0.7cm) 1000/0.15, (2cm) 400/0.3.

Table IV.3(b). Maximum and minimum values of baseline lengths and r.m.s. noise in correlated flux density for the U.S. network. Baselines are indicated in parentheses (m-n), according to the key below the table.

Wavelength(cm)	Baseline length ($10^6\lambda$) max		min		RMS Noise in Correlated Flux Density (mJy) max	min
	equat.	polar	equat.	polar		
1.3	300	35 (4-6)	59	11 (2-4)	250(4-6)	140(2-6)
2.8	139	16 (4-6)	27	5.1(2-4)	470(1-4)	70(2-6)
3.8	108	3.9(3-4)	9.8	8.1(3-6)	520(1-3)	90(2-4)
6	57	3.4(2-3)	6.2	5.2(3-6)	220(1-3)	90(2-3)
13	30	3.5(4-6)	5.2	1.1(2-7)	250(4-7)	130(2-6)
18	23	0.8(3-4)	2.0	0.8(5-7)	480(1-4)	60(2-6)
21	16	1.0(2-3)	1.8	1.5(3-6)	420(3-5)	50(2-6)
50	6.7	0.2(2-6)	2.8	1.2(1-6)	510(1-6)	250(2-6)

The r.m.s. noise has been calculated assuming MK II VLBI systems, 2 MHz bandwidth, and 60 seconds coherent integration time. For longer integration times (T) multiply the value given by $\sqrt{60/T}$.

Baseline key: 1. Fort Davis; 2. Green Bank; 3. Hat Creek; 4. Haystack; 5. North Liberty; 6. Owens Valley; 7. Vermilion River.

Table IV.4(a). Observatories used for VLBI in Europe: System noise temperature (^{o}K) and aperture efficiency listed as a function of wavelength on 1 July 1979.

Observatory	Antenna Diam.(m)	Observing wavelength (cm) 1.3	2.8	6	11	18	21
Cambridge (England)	32 (equiv.diam.)			90 0.82	75 0.8		
Chilbolton (England)	25	1300 0.3	180 0.5	100 0.5			
Crimea (USSR)	22	100 0.4	100 0.4	200 0.5		250 0.5	
Dwingeloo (Netherlands)	25		480 0.12	60 0.44		37 0.60	42 0.60
Effelsberg (Germany)	100	200 0.15	75 0.40	80 0.47	100 0.5	60 0.50	100 0.50
Jodrell Bank (England)	76(MKIA) 25x38(MKII) 25(Knockin)	500 0.5 (Knockin)		60 0.50$^{\neq}$ (MKII)	100 0.40	60 0.50	60 0.50
Onsala (Sweden)	26,20	100 0.5 (20m)		45 0.5 (26m)		25 0.5 (26m)	
Westerbork (Netherlands	93 (equiv.diam.)		450 0.21$^{\oplus}$	80 0.48			95 0.54

≠ Illuminated as a 25 m circular aperture. ⊕ One 25m antenna.

Other wavelengths: Cambridge (0.95cm) 1300/0.4, (2cm) 175/0.6; Effelsberg (2cm) 80/0.20, (0.95cm) 1500/0.1; Jodrell Bank (13cm) 100/04, (50cm) 100/0.6; Onsala (0.7cm, 20m) 1000/0.5, (0.95cm, 20m) 200/0.5, (3.6cm, 20m) 170/0.5, (3.7cm, 26m) 60/0.15, (13cm, 26m) 100/0.5; Westerbork (50cm) 320/0.59.

Table IV.4(b). Maximum and minimum values of baseline lengths and r.m.s. noise in correlated flux density for the European baselines. Baselines are indicated in parentheses (m-n) according to the key below the table.

Wavelength(cm)	Baseline length ($10^6\lambda$) max		min		RMS Noise in Correlated Flux Density (mJy)	
					max	min
	equat.	polar	equat.	polar		
1.3	207	48 (3-6)	24	11 (2-6)	2670(2-6)	210(5-7)
2.8	87	17 (2-3)	7.2	5.6(4-5)	1030(2-8)	80(3-5)
6	45	10 (3-6)	3.3	2.6(4-5)	410(2-3)	14(5-8)
11	6.1	1.7(5-6)	1.7	0.6(1-6)	150(1-6$^{\otimes}$)	24(5-6)
18	15	3.4(3-6)	1.1	0.9(4-5)	360(3-6$^{\otimes}$)	25(5-7)
21	3.2	0.9(5-6)	0.9	0.8(4-5)	120(4-6$^{\otimes}$)	16(5-8)

The r.m.s. noise has been calculated assuming MK II VLBI systems, 2 MHz bandwidth, and 60 seconds coherent integration time. For longer integration times (T) multiply the values given by $\sqrt{60/T}$.

Baseline key: 1. Cambridge; 2. Chilbolton; 3. Crimea; 4. Dwingeloo; 5. Effelsberg; 6. Jodrell Bank (MK IA antenna); 6$^{\otimes}$. Jodrell Bank (MK II antenna); 7. Onsala; 8. Westerbork.

notable gaps in u,v coverage by addition of one or more new antennas (Swenson 77 Univ. of Illinois Report, VLBI network studies IV; Phillips and Mutel 77 Univ. of Iowa Report no. 77-20) and more ambitious plans for a dedicated array (Swenson and Kellermann 75 Sci 188, 1263; Kellermann 77 NRAO Report, VLBI network studies III). A similar array of up to 7 existing telescopes has been organized in Europe, including one station in the USSR, and studies of possible satellite-linked operation have been made (Olthoff 78 ESA Report DP PS (78)15). Proposals for dedicated VLBI arrays have been made in Canada (Legg 78 paper presented at US National Science Meeting, Boulder, 6 Nov.) and the Peoples' Republic of China (Wan Tung-Shan, private communication to M.H. Cohen 1978).

The four tables in this section summarize the essential characteristics and capacities of the North American and European arrays. For many important experiments (parts of) these two arrays are combined as a versatile transatlantic network.

V. RADIO ASTRONOMY INSTRUMENTATION

Brian J. ROBINSON; CSIRO Radiophysics.

a) Low Noise Receivers ($\nu < 50$ GHz)

(i) Masers. - Tunable travelling-wave masers (TWM) using rutile for the frequency ranges 20-25 GHz and 29-35 GHz have been developed in Sweden (Kollberg and Lewin 76 IEEE Trans. MTT-24, 718), with a new type of dielectric imageline slow-wave structure that is superior to the dielectrically loaded waveguide. At the imput flange T_N is 27 K and the bandwidth 30 to 60 MHz. In the USA (Yngvesson et al. 76 IEEE Trans. MTT-24, 711) a 22 GHz TWM using a photo-etched slow-wave structure on ruby has T_S = 80 K and bandwidth = 40 MHz. In the USSR (Abramyan and Martiroayan 74 Radiotec Electr 19, 207) a two-resonance maser at 22 GHz has been developed with a low-frequency pump.

TWM are installed on radome-enclosed telescopes in Brazil, Sweden and the USA for radiospectroscopy at 22 GHz. In each case the zenith system temperature is about 100 K. The TWM bandwidth is restricted by the line width of the maser crystal, and for continuum measurements the TWM has a lower sensitivity than the parametric amplifier since $T_N/\sqrt{B}$ is worse.

Broadband, tunable, reflection-type masers have been developed in the USA at 10 GHz (Flesner et al. 77 Rev Sci Instrum 48, 1104) and for the band 18-25 GHz. These masers operate at 4 K and so can use a closed-cycle refrigeration system. A block of 8 masers operating in series, connected by circulators, has demonstrated an instantaneous bandwidth of 250 MHz. However, there are large (10 x) gain ripples across the band (Presumably the result of limited isolation in the circulators) which would be a serious drawback in radio astronomy applications.

(ii) Parametric up-converters. - An input frequency f_i to a variable-capacitance amplifier pumped at f_p produces an output at $f_o = f_p + f_i$ with gain $G \leqslant f_o/f_i$. This up-converter has matched input and output and (with its low gain) offers wide bandwidth and very high stability. Cryogenically-cooled up-converters are used (Weinreb et al. 77 IEEE Trans. MTT-25, 243) on the VLA in New-Mexico, and on other telescopes, with $1.3 < f_i < 1.7$ GHz and $f_o = 5$ GHz; measured performance is $T_N = 8$ K, $G = 4$ dB and bandwidth > 200 MHz. With a 5 GHz cryogenic parametric amplifier as a second stage an overall noise temperature of 17 K has been achieved. Operating system temperatures at 1.4 GHz are 48 K (VLA), 39 K (Nançay) and 35 K (Dwingeloo).

The low second-stage noise offered by a maser has stimulated the development of up-converters at other frequencies. Bench tests on a cryogenically-cooled up-converter with $8.2 \text{ GHz} \leqslant f_i \leqslant 10.8$ GHz and $f_o = 22$ GHz indicate that (at 80 K) T_N should be about 13 K, gain ≈ 2 dB and bandwidth = 300 MHz.

(iii) FET amplifiers. - Considerable development of cryogenically-cooled GaAs Field Effect Transistor (FET) amplifiers has led to cheap, low-noise, wide-bandwidth amplifiers suitable for second- or third-stages in low-noise systems. Measurements at Berkeley are tabulated below.

Frequency (GHz)	Noise Temperature		Bandwidth (MHz)
	At T = 290 K	At T = 80 K	
1.4 to 1.7	53 K	25 K	150
5.0	80 K	30 K	500

FET amplifiers have been operated at frequencies as high as 18 GHz. At 15 GHz the predicted T_N is about 100 K at liquid nitrogen temperature. For some commercial FET amplifiers at 5 GHz the micro-strip has failed after temperature cycling.

b) Millimetre-Wave Receivers.

(i) Schottky-barrier mixers. - Most operational mm-wave receivers are using GaAs Schottky-barrier mixers at cryogenic temperatures. Manufacture of the mixer chips remains a black art, and even mounting and whiskering of mixers is confined at present to a handful of laboratories. At a temperature of 20 K, T_N = 550 K to 600 K (SSB) has been achieved at frequencies from 80 to 115 GHz in the USA, Germany and Australia. For room temperature operation at 115 GHz, T_N of 860 K to 1200 K (SSB) have been reported (Cong and Kerr 78 IEEE Trans. MTT-26,Dec.; Wilson 77 IEEE Trans. MTT-25, 332).

Improved performance has been reported (Linke et al. 78 IEEE Trans. MTT-26,Dec.) for GaAs mixer diodes prepared by molecular beam epitaxy. At 80 GHz T_N = 312 K (SSB) for a mixer cooled to 18 K followed by a cooled 5 GHz parametric amplifier (IF noise = 22 K). The low mixer noise temperature (T_m = 209 K) is attributed to an absence of parametric effects since the diodes show little change in capacitance with voltage. Low noise operation also resulted from short-circuiting of the noise entering the image port.

(ii) Millimetre-wave masers. - In the USSR andalusite has been used successfully for a 6 mm wavelength maser. In the USA a travelling-wave rutile maser designed for 85 GHz has been operated (Cardiasmenos et al. 76 IEEE Trans. MTT-24, 725) on the bench with a gain of 15 dB and instantaneous bandwidth of 50 MHz. Three rutile transitions were pumped simultaneously at frequencies between 46 and 115 GHz. The need for power at high pump frequencies is a major limitation on mm-wave masers.

(iii) Josephson junction devices. - Numerous attempts have been made to realise the low-noise potential of Josephson junctions. The use of junctions as mixers at 47 GHz and 300 Ghz had not reached the expected goal (Edrich 76 IEEE Trans. MTT-24, 706; Edrich et al. 77 IEEE Trans. MTT-25, 476). A junction was operated as a parametric amplifier (Chiao and Parrish 76 J Appl Phys 47, 2639) at 33 GHz, but the results could not be reproduced with later junctions.

Recently Nb point-contacts have been successfully tested (Taur and Kerr 78 Appl Phys Lett 32 775) as low-noise mixers at 115 GHz. For a junction at 6 K the measured mixer noise temperature T_m = 120 K (SSB) with unity conversion efficiency; only 2 to 3 nW of L.O. power was incident on the junction. The T_m is within a factor of two of the theoretically predicted performance. With a suitable second stage a receiver T_N of 220 K (SSB) should be achieved; slight gain (1 to 2 dB) in the mixer could reduce T_N to 150 K.

Above 115 GHz a roughly linear rise of T_N is predicted, reaching 600 K at 500 GHz, provided that efficient RF coupling to the junction is maintained at such frequencies. The main disadvantage of the Josephson junction is its extremely low saturation power, around 10^{-9} watts.

(iv) Parametric down-converters. - A variable-capacitance down-converter from 115 to 22 GHz has been tested at NRAO with a maser second stage. Conversion loss is about 12 dB, and a T_N of 270K was measured on one occasion. The expected T_N was 185K.

(v) Quasi-optic techniques. - At mm-wavelengths quasi-optic techniques have come into use to reduce the loss associated with waveguide components and to realise filters, diplexers, etc. Quasi-optic systems have been built (Goldsmith 77 Bell Sys Tech J 56, 1483; Erickson 77 IEEE Trans. MTT-25, 865) for signal and local oscillator injection and image rejection (Wannier et al. 76 Rev Sc Instrum 47, 56).

c) Correlators and Spectrometers.

(i) Digital correlators.- A 5120 channel spectral line correlator for the Westerbork synthesis telescope has increased the backend capability to 64 complex channels for 40 interferometers (previously 8 x 10). The spectral resolution can be selected from 1.2 to 156 kHz. The system uses 1-bit, 2-bit or 1-times 2-bit correlation, sacrificing a factor of 2 in resolution for the 2-bit mode. In the continuum mode the correlator increases the bandwidth from 4 to 10 MHz.

Half of the VLA digital spectral processor has been completed, providing all possible correlation between 27 antennas with two IF channels per antenna (4 later). The concept of the recirculating correlator is used to provide spectral resolutions from 16 channels over 50 MHz to 512 channels over 100 kHz. Custom-designed integrated circuits (a dual 2-bit multiplier and a 12-bit integrating counter) have been produced successfully. For continuum operation the processor offers bandwidths up to 50 MHz.

At NRAO the VLA IC chips are being used for a 1024 channel correlator with a maximum bandwidth of 80 MHz.

In Australia an asynchronous correlator is being studied, consisting of a chain of identical modules, one per channel. Each module is connected only to its immediate neighbours in the chain, greatly reducing the interconnection problem in a standard correlator. The clock signal for each module is derived from the preceding module, so each operates at its own local clock phase, thus avoiding the need for clock synchronization over the entire machine. A suitable circuit design and logic technology are being determined for a prototype integrated circuit.

A new digital backend is being built for the Fleurs Synthesis Telescope to allow simultaneous operation of the 1600 m E-W array and the N-S array and result in r.m.s. noise less than 5 mJy for 8 hours observing. The backend uses a zero-frequency I.F. system, taking four correlations to recover the signal/noise ratio loss due to folding. The backend can be configured to allow real time operation of the grating cross for solar observations.

(ii) Filter banks. - The NRAO design of filter bank has excellent performance in terms of sensitivity, stability and flexibility, and has been copied at a number of other observatories. 256 channels are available, with a choice of spectral resolution from 100, 250, 500 to 1000 kHz. When only a coarse filter bank is available, higher resolution can be achieved (Henry Rev Sc Instrum, in press) by a "spectrum expander" using a loop memory, with a noise penalty of only a few per cent.

(iii) Acousto-optic spectrograph. - At mm-wavelengths the fastest digital correlator in use has insufficient bandwidth, and filter banks are widely used (see ii). However, the acousto-optic spectrograph (AOS) has been used successfully in Australia (Milne and Cole 77 IREE (Aust) Int Conv Record 295-298) and Japan (Kaifu et al. 77 PASJ 29, 429) to obtain good frequency resolution and wide frequency coverage. Characteristics of some operating AOS are tabulated here:

Parameter	AOS model		
	CSIRO	Tokyo 1	Tokyo 2
Ultrasonic material	Quartz	TeO_2	TeO_2
Centre frequency (MHz)	135	65	360
Overall bandwidth (MHz)	90	41	200
Number of channels	512	1728	1728
Frequency resolution (kHz)	240	38	250
IF drive power (mW)	150	10	500
Frequency drift rate	7 kHz/hour	20 kHz/day	50 kHz/day
Linearity	<1%	<2%	<3%
Readout noise level (dB)	-24	-	-

With beam-switching at a 2 sec rate the AOS sensitivity has been measured as 95% of that of a filter bank under the same operating conditions. Thermal drifts and mechanical vibration have been reduced to the point where 20 hour integrations have been made.

d) IF Transmission Systems.

The VLA uses a circular waveguide IF distribution system (Weinreb et al. 77 Microwave J 20, 49), now in operation over a 13.6 km length. The laying technique results in small curvature and subsidence, with an attenuation at 50 GHz of 1.1 dB per km which remains stable. A short length of reduced diameter waveguide prevents TW_{02} mode propagation.

In modifications to the Parkes interferometer for synthesis operation the analog signal is converted to a digital bit-stream at the antenna focii. This obviates the need for highly-stable IF cables. The sampling clock at each focus is Doppler-shifted to stop the fringes and to ensure that the sample instants at the receivers are matched across the wave fronts from the field centre. Delay compensation is achieved digitally by passing the two bit-streams through first-in first-out memory stacks.

e) Processing Hardware.

Development work is continuing in Australia on special purpose digital hardware for synthesis data reduction (Frater and Skellern 78 AA 68, 391; Frater 78 AA 68, 397). A 256 x 256 point map is produced in 20 seconds from data for 720 hour angles. The system copes readily with any linear array regardless of orientation, and can be readily adapted for other arrays. Hardware is also being developed for "cleaning" and a real-time display has been made for interactive use. A 64 x 64 data array is scanned and processed to produce a 256 x 256 point display with a choice of contour, ruled surface or intensity format.

Hybrid analogue/digital approaches to the processing of aperture synthesis data are also being explored in Australia (Cole 79 IAU Coll 49). The techniques have included computer-generated holograms, electro-optics and surface acoustic waves.

In the Netherlands a hybrid digital/analog processor is being tested for "quick and dirty" map making.

An acoustic-optic image processor (Kai and Kosugi IAU Coll 49) has been tested in Japan on a 160 MHz compound interferometer. Eleven acousto-optic light modulators, each connected to an antenna, are arranged to form an array analogous to the antenna array on a reduced scale (4 mm spacing). A collimated laser beam is diffracted by the modulators to form an image on a 256 photodiode array.

VI. DATA PROCESSING AND DATA DISPLAY.

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Introduction. - The boundary between "on-line" and "off-line" data processing in radio astronomy is vague, and also shifts in the course of time. Operations on the data which used to be the responsibility of the observer himself have, at some radio observatories, become so well known and routine that they have been incorporated into the standard reduction procedures over which the observer has rather little control. For instance at Westerbork, routine calibration of the entire instrument (baseline vectors, receiver gain, collimation) is handled entirely by observatory staff. At the 5 km telescope in Cambridge, even the Fourier transformation of the calibrated data to produce the sky maps is carried out "on-line", so that the radio astronomer receives his sky maps directly from the telescope.

During the past few years the observer's attention has moved to points further down the reduction chain, to the problems of recognizing and removing low-level residual observational and instrumental inaccuracies, experimenting with restoration algorithms designed to more-or-less remove the instrumental response function from the maps, and displaying large amounts of multi-dimensional data.

Single-dish map processing. - In addition to the usual problems of slow variations in receiver gain and noise factor, observations at centimetric wavelengths are affected by variations in tropospheric attenuation. Two new methods have been developed at the Max Planck Institute for Radio Astronomy in Bonn for improving the quality of the maps obtained from high-sensitivity observations of extended low-surface brightness regions:

a) An interesting extension of the well known dual-beam observation method has been reported by Emerson et al. (79 AA in press). This method shows much promise, also for mapping extended regions of angular size greater than the separation between the beam centers.

b) A second technique makes use of pairs of maps of the same region, scanned in orthogonal directions. In the case where the baseline and gain drift along the scan direction are much better defined than from one scan to the next, a polynomial baseline correction procedure called "Basket Weaving" has been developed by C.J. Salter. The success of the method rests with the fact that the astronomically interesting structure is well correlated between the two maps, whereas the scan baseline errors are not.

A restoration method for single-dish data has been developed by Reich et al. (78 AA 69 165). It makes use of the rotation of the telescope beam parallactic angle in an az-el system during the course of a mapping operation in order to achieve an identification and hence a removal of the sidelobes. The technique permits the study of weak extended emission in the presence of strong nearby radio sources.

Work is also proceeding towards the development of a recommended international standard for exchanging radio map data in machine-readable form based on the NOD2 reduction programs (Haslam 74 AA Sup 15, 333).

Synthesis map processing. - The increase of activity over the past few years in the general area of processing interferometer observations into synthesized maps was amply illustrated by the activities during the joint URSI/IAU Colloquium no. 49, held in Groningen in 1978. The Proceedings of that colloquium (Van Schooneveld 79) are an excellent source for up-to-date information of a sort which otherwise does not often find its way into the astronomical literature.

1. Restoration algorithms. The "CLEAN" procedure has been analysed mathematically by Schwarz (78 AA 65, 345) and conditions for convergence discussed. Although the method is quite successful for fields consisting of a few discrete sources, several contradictionary results obtained on real observations of complicated fields over the past few years have shown that the present widespread use of this restoration

algorithm is not a sufficient condition to guarantee the correctness of the maps which it produces. The procedure can undoubtedly accurately represent the data in those areas of the u,v plane where observations were actually made; unfortunately, there is as yet no general method available for evaluating the relevance of the information produced by CLEAN in other areas of the u,v plane. Theoretical work on this problem is continuing. There remains a good deal to be said for actually obtaining the missing information by measurements if at all possible.

The efficacy of the various criteria used in maximum-entropy method ("MEM") approaches was (even passionately) debated at IAU Colloquium No. 49; the reader is referred to the Proceedings for details. The MEM procedure is more complex and time-consuming than CLEAN. It also suffers from the lack of criteria for evaluating the relevance of the concocted information; the statement by proponents of MEM that the method makes a minimum of *a priori* assumptions about this information (hence the term "maximum entropy") offers a philosophical condolence to the observer which is unfortunately of little practical value to him.

The continuing difficulties in maintaining relative phase stability over long periods of time in VLBI observations have provided the impetus for a methodical development of the "closure-phase" technique by Readhead and Wilkinson (78 ApJ 223, 25). The method offers a way of iterating an initial guess at a model of the relative distribution of sources in the field towards the observed data with the help of CLEAN and the limited visibility function phase information which is available in the closure phase relations.

Interest in the restoration of maps made without any interferometer phase information has been revived after a ∿ 15-year period of relative neglect on the part of radio astronomers. This time the problems are not instrumental instabilities, but fundamental limitations on the phase stability imposed by the ionosphere below 300 MHz and by the atmosphere above 1 GHz. A method of restoration which is well known to X-ray crystallography and to optical holography has been introduced to radio astronomers by Baldwin and Warner (76 MN 175, 345); the method makes use of the strongest symmetric discrete sources in the observed field to provide a positional reference for the rest. Extension to more general source distributions has also been considered (Baldwin and Warner 78 MN 182, 411).

2. Dynamic range limitations. - As radio astronomers continue to dig ever deeper into the noise in order to recover the astrophysically interesting information (especially on extended sources), the limitations set by atmospheric/ionospheric and instrumental instabilities are appearing even in maps made with carefully - engineered phase - stable synthesis telescopes. The best dynamic range currently obtainable for instance in routine observations at Westerbork is about 23 dB, with perhaps one or two more factors of 2 in the case of channel-to-channel comparisons in spectrometer observations. A thorough investigation into the problems has been made by Hamaker (79 IAU Colloquium No. 49, Reidel); the different short- and longer-time scale instabilities produce different clearly-recognizable patterns around strong discrete sources in the maps. In some cases, simple models of the phase instabilities can be fitted to these patterns and the effects thereby largely removed. It is worth pointing out that the large-scale, regular nature of these instrumental features on the maps is (of course) due to the corresponding high degree of regularity with which the Westerbork telescope samples the u,v plane. Even the job of simply first deciding what went wrong will not be as easy with synthesis instruments which lack this regularity.

3. Map display. - With most single-dish maps at the present time the display problem is solved as soon as one finds a way of drawing contour maps neatly, be that by a computer or by a draftsman. This "classical" approach fails for the case of modern-day high resolution synthesis maps where the quantity of data is such that no meaningful contour representation is possible; the situation and a number of alternatives have been discussed recently by the author (79 IAU Coll.49). In an interactive data processing system the problem is further aggravated by the additional requirements for a rapid display of the interim results; photographic

recording is just too slow in this case. The potential value of the methods and machines currently used to interactively analyse and display satellite photographs of the earth has been recognized by many astronomers, and the first applications to the treatment of optical plates at the KPNO (contact Dr. D. Wells) have been very successful. The price of these machines has now decreased to the point where they are within the reach of the average radio astronomy research institute, and the number of applications to radio synthesis map processing and display is increasing. At the present time, COMTAL video display devices are operational at the NRAO/VLA site (contact Dr. R. Hjellming) and at Leiden Observatory (contact Dr. P. Katgert). The NRAO/VLA system includes an array processor and a vector graphics system. An I^2S Model 70E image computer has recently been installed at the Kapteyn Laboratory in Groningen, coupled with an IPS video disk for the storage and cinematographic playback of large numbers of processed images (contact the author). Research into the effective use of these devices is just now beginning; the next few years should produce many novel approaches to the use of colour and cinematography for display, and to exploiting the memory capacity and processing power of the new generation of machines.

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